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# Search for a massive resonance decaying into a Higgs boson and a W or Z boson in hadronic final states in proton-proton collisions at $\sqrt{s} = 8$ TeV



## The CMS collaboration

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**ABSTRACT:** A search for a massive resonance decaying into a standard-model-like Higgs boson (H) and a W or Z boson is reported. The analysis is performed on a data sample corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ , collected in proton-proton collisions at a centre-of-mass energy of 8 TeV with the CMS detector at the LHC. Signal events, in which the decay products of Higgs, W, or Z bosons at high Lorentz boost are contained within single reconstructed jets, are identified using jet substructure techniques, including the tagging of b hadrons. This is the first search for heavy resonances decaying into HW or HZ resulting in an all-jet final state, as well as the first application of jet substructure techniques to identify  $H \rightarrow WW^* \rightarrow 4q$  decays at high Lorentz boost. No significant signal is observed and limits are set at 95% confidence level on the production cross sections of  $W'$  and  $Z'$  in a model with mass-degenerate charged and neutral spin-1 resonances. Resonance masses are excluded for  $W'$  in the interval [1.0, 1.6] TeV, for  $Z'$  in the intervals [1.0, 1.1] and [1.3, 1.5] TeV, and for mass-degenerate  $W'$  and  $Z'$  in the interval [1.0, 1.7] TeV.

**KEYWORDS:** Hadron-Hadron scattering, Beyond Standard Model, Particle and resonance production, Higgs physics

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**1 Introduction**

Several theories of physics beyond the standard model (SM) predict the existence of vector resonances with masses above 1 TeV that decay into a W or Z vector boson (V) and a SM-like Higgs boson (H). Here we present a search for the production of such resonances in proton-proton (pp) collisions at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV. The data sample, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ , was collected with the CMS detector at the CERN LHC.

The composite Higgs [1–3] and little Higgs models [4–6] address the hierarchy problem and predict many new particles, including additional gauge bosons, e.g. heavy spin-1  $W'$  or  $Z'$  bosons ( $V'$ ). These models can be generalized in the heavy vector triplet (HVT) framework [7]. Of particular interest for this search is the HVT scenario B model, where the branching fractions  $\mathcal{B}(W' \rightarrow WH)$  and  $\mathcal{B}(Z' \rightarrow ZH)$  dominate over the corresponding branching fractions to fermions, and are comparable to  $\mathcal{B}(W' \rightarrow WZ)$  and  $\mathcal{B}(Z' \rightarrow WW)$ . In this scenario, experimental constraints from searches for boson decay channels are more stringent than those from fermion decay channels. Several searches [8–12] for  $W' \rightarrow WZ$  based upon the Extended Gauge Boson (EGB) reference model [13] have excluded resonance masses below 1.7 TeV. Unlike the HVT scenario B model, the EGB model has enhanced fermionic couplings and the mass limit is not directly comparable to this work. Model independent limits on the cross section for the resonant production  $\ell\nu + \text{jets}$  [14] can be used to extract resonance mass limits on the processes  $W' \rightarrow WZ$  and  $Z' \rightarrow WW$  of

1.7 TeV and 1.1 TeV, respectively. A search for  $Z' \rightarrow ZH \rightarrow q\bar{q}\tau\tau$  was reported in ref. [15] and interpreted in the context of HVT scenario model B; however, no resonance mass limit could be set with the sensitivity achieved. Finally, a recent search [16] combining leptonic decays of W and Z bosons, and two b-tagged jets forming a  $H \rightarrow b\bar{b}$  candidate excluded HVT model A with coupling constant  $g_V = 1$  for heavy vector boson masses below  $m_{V^0} < 1360$  GeV and  $m_{V^\pm} < 1470$  GeV.

The signal of interest is a narrow heavy vector resonance  $V'$  decaying into  $VH$ , where the  $V$  decays to a pair of quarks and the  $H$  decays either to a pair of b quarks, or to a pair of W bosons, which further decay into quarks. The  $H$  in the HVT framework does not have properties that are identical to those of a SM Higgs boson. We make the assumption that the state observed by the LHC Collaborations [17, 18] is the same as the one described by the HVT framework and that, in accord with present measurements [19, 20], its properties are similar to those of a SM Higgs boson.

In the decay of massive  $V'$  bosons produced in the pp collisions at the LHC, the momenta of the daughter  $V$  and  $H$  are large enough ( $>200$  GeV) that their hadronic decay products are reconstructed as single jets [21]. Because this results in a dijet topology, traditional analysis techniques relying on resolved jets are no longer applicable. The signal is characterized by a peak in the dijet invariant mass ( $m_{jj}$ ) distribution over a continuous background from mainly QCD multijet events. The sensitivity to b-quark jets from  $H$  decays is enhanced through subjet or jet b tagging [22]. Jets from  $W/Z \rightarrow q\bar{q}'$ ,  $H \rightarrow b\bar{b}$ , and  $H \rightarrow WW^* \rightarrow 4q$  decays are identified with jet substructure techniques [23, 24].

This is the first search for heavy resonances decaying via  $VH$  into all-jet final states and it incorporates the first application of jet substructure techniques to identify  $H \rightarrow WW^* \rightarrow 4q$  at a high Lorentz boost.

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [25].

## 3 Signal model and simulation

In the HVT framework, the production cross sections of  $W'$  and  $Z'$  bosons and their decay branching fractions depend on three parameters in addition to the resonance masses: the strength of couplings to quarks ( $c_q$ ), to the  $H$  ( $c_H$ ), and on their self-coupling ( $g_V$ ). In the HVT model B, where  $g_V = 3$  and  $c_q = -c_H = 1$ ,  $W'$  and  $Z'$  preferentially couple to

bosons (W/Z/H), giving rise to diboson final states. This feature reproduces the properties of the  $W'$  and  $Z'$  bosons predicted by the minimal composite Higgs model. In this case, the production cross sections for  $Z'$ ,  $W'^-$ , and  $W'^+$  are respectively 165, 87, and 248 fb for a signal of resonance mass  $m_{V'} = 1$  TeV. Their branching fractions to VH and decay width are respectively 51.7%, 50.8%, 50.8% and 35.0, 34.9, 34.9 GeV. The resonances are assumed to be narrow, i.e., with natural widths smaller than the experimental resolution in  $m_{jj}$  for masses considered in this analysis.

We consider the  $W'$  and  $Z'$  resonances separately, and report limits for each candidate individually to permit the reinterpretation of our results in different scenarios with different numbers of spin-1 resonances.

Signal events are simulated using the MADGRAPH 5.1.5.11 [26] Monte Carlo event generator to generate partons that are then showered with PYTHIA 6.426 [27] to produce final state particles. These events are then processed through a GEANT4 [28] based simulation of the CMS detector. The MADGRAPH input parameters are provided in ref. [29] and the H mass is assumed to be 125 GeV. Samples showered with HERWIG++ 2.5.0 [30] are used to evaluate the systematic uncertainty associated with the hadronization. Tune Z2\* [31] is used in PYTHIA, while the version 23 tune [30] is used in HERWIG++. The CTEQ6L1 [32] parton distribution functions (PDF) are used for MADGRAPH, PYTHIA and HERWIG++. Signal events are generated from resonance mass 1.0 to 2.6 TeV in steps of 0.1 TeV. Signals with resonance masses between the generated values are interpolated.

The distribution of the background is modelled from the data. However, simulated samples of multijet and  $t\bar{t}$  events, generated using MADGRAPH 5v1.3.30 [26] and POWHEG 1.0 [33–35], respectively, and interfaced to PYTHIA for parton showering and hadronization, serve to provide guidance and cross-checks.

## 4 Event reconstruction and selection

The event selection, in the online trigger as well as offline, utilizes a global event description by combining information from the individual subdetectors. Online, events are selected by at least one of two specific triggers: one based on the scalar sum of the transverse momenta  $p_T$  of the jets ( $H_T$ ), which requires  $H_T > 650$  GeV; the other on the invariant mass of the two jets with highest  $p_T$ , which requires  $m_{jj} > 750$  GeV.

The offline reconstruction is described below.

Events must have at least one primary vertex reconstructed with  $|z| < 24$  cm. The primary vertex used in the event reconstruction is the one with the largest summed  $p_T^2$  of associated tracks. Individual particle candidates are reconstructed and identified using the particle-flow algorithm [36, 37], and divided into five categories: muons, electrons, photons (including those that convert into  $e^+e^-$  pairs), charged hadrons, and neutral hadrons. Charged particle candidates associated with a primary vertex different from the one considered for the event reconstruction are discarded, which reduces contamination from additional pp interactions in the same bunch crossings (pileup).

Jets are clustered from the remaining particle flow candidates, except those identified as isolated muons, using the Cambridge-Aachen (CA) [38, 39] jet clustering algorithm as

implemented in FASTJET [40, 41]. This algorithm starts from a set of particles as “protojets”. It combines them iteratively with each other into new protojets until the distance of the resulting protojet to the closest remaining protojet is larger than the distance parameter of the CA algorithm. A distance parameter of 0.8 is used (CA8 jets). An event-by-event correction based on the jet area method [42–44] is applied to remove the remaining energy deposited by neutral particles originating from pileup. The pileup-subtracted jet four-momenta are then corrected to account for the difference between the measured and true energies of hadrons [44]. Jet identification criteria [45] are applied to the two highest  $p_T$  jets in order to remove spurious events associated with calorimeter noise.

The jet reconstruction efficiencies (estimated from simulation) are larger than 99.9%, and contribute negligibly to the systematic uncertainties for signal events.

Events are selected by requiring at least two jets each with  $p_T > 30$  GeV/ $c$  and pseudorapidity  $|\eta| < 2.5$ . The two highest  $p_T$  jets are required to have a pseudorapidity separation  $|\Delta\eta| < 1.3$  to reduce background from multijet events [46]. The invariant mass of these two jets is required to satisfy  $m_{jj} > 890$  GeV/ $c^2$ . The trigger efficiency for the events passing the preselection requirements exceeds 99%.

To enable the results to be applied to other models of similar final states, we utilize simulations to derive the geometrical acceptances and the W/Z and H selection efficiencies. These are presented separately in figures 1, 6, and 7, respectively.

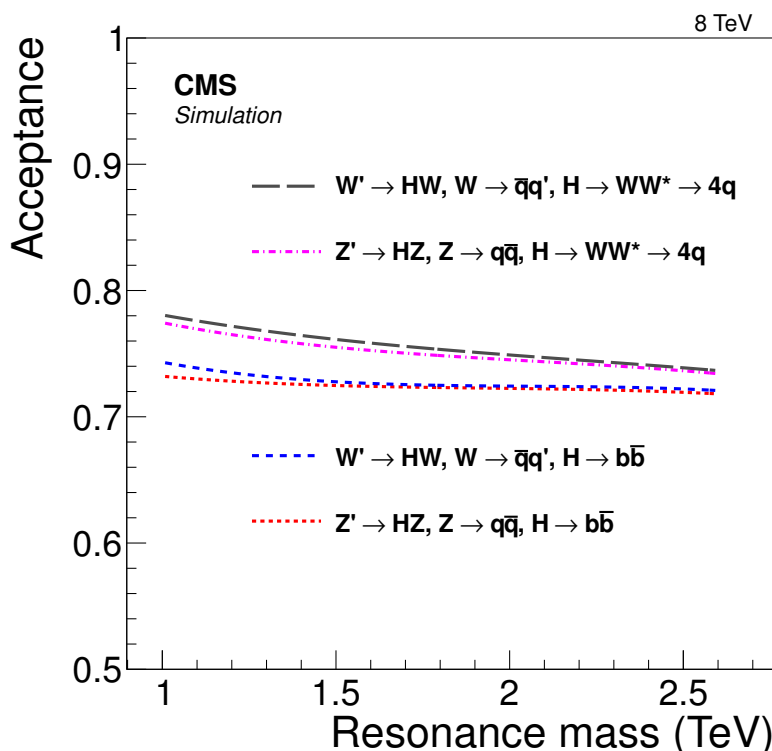
For the purpose of reinterpreting the result, the global efficiency is presented approximated by the product of acceptances and the W/Z and H selection efficiency, restricted to final states where the W/Z and H bosons decay hadronically. The products of acceptances and the W/Z and H tagging efficiency, ignoring the correlations between detector acceptance and W/Z or H tagging, agree to better than 10% with the full event simulation. In the interpretations reported in this paper, the global efficiency is estimated from the full simulation of signal events, such that the correlations between the acceptance and W/Z and H selection efficiency are properly taken into account. However, when re-interpreting this search in terms of an arbitrary model, an additional uncertainty of 10% should be folded in, to allow for the possible effect of correlations.

The acceptance, shown in figure 1 as a function of the dijet resonance mass for several signals, takes into account the angular acceptance ( $|\eta| < 2.5$ ,  $|\Delta\eta| < 1.3$ ).

The two highest  $p_T$  jets are chosen as candidates for the hadronically decaying W/Z and H bosons, and W/Z and H tagging algorithms based on jet substructure are applied.

Information characterizing jet substructure is derived using three separate algorithms, producing the variables *pruned jet mass*, *subset b tagging*, and *N-subjettiness*. The combined use of these variables in event selection strongly suppresses the background from QCD dijet production. All three characterizations of jet substructure are defined and discussed in detail in the following paragraphs.

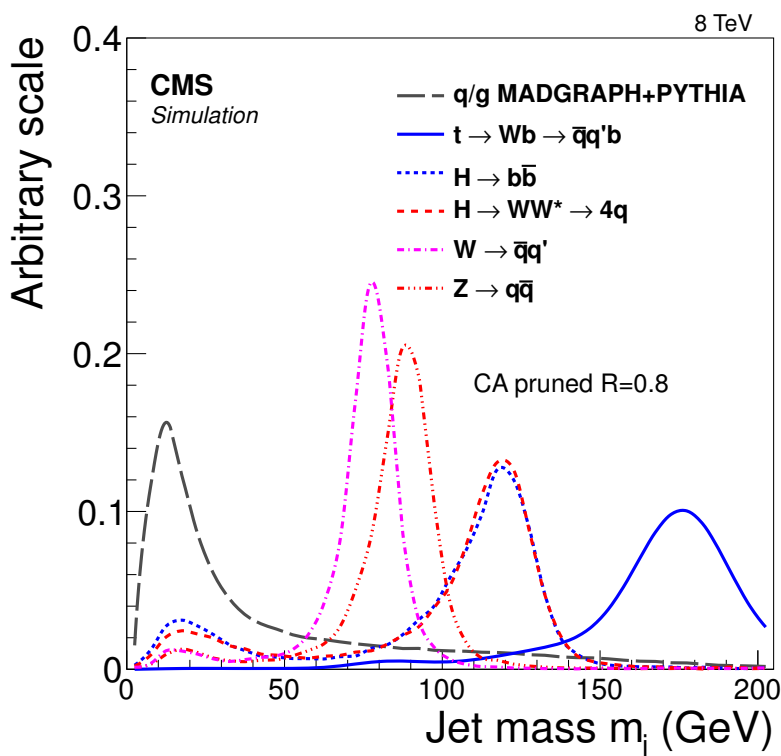
As the mass of the V or H boson is larger than the mass of a typical QCD jet, the jet mass is the primary observable that distinguishes such a jet from a QCD jet. The bulk of the V or H jet mass arises from the kinematics of the two or more jet cores that correspond to the decay quarks. In contrast, the QCD jet mass arises mostly from soft gluon radiation. For this reason, the use of jet pruning [47, 48] improves discrimination



**Figure 1.** The fraction of simulated signal events for hadronically decaying W/Z and H bosons, reconstructed as two jets, that pass the geometrical acceptance criteria ( $|\eta| < 2.5$ ,  $|\Delta\eta| < 1.3$ ), shown as a function of the resonance mass.

by removing the softer radiation, as this shifts the jet mass of QCD jets to smaller values, while maintaining the jet mass for V and H jets close to the masses of W, Z or H bosons. Jet pruning is implemented by applying additional cuts in the process of CA jet clustering. These cuts remove protojets that would have a large angle and low  $p_T$  with respect to the combination with another protojet. The details of this procedure are given in ref. [24]. The distributions of the pruned jet mass ( $m_j$ ) for simulated signal and background samples, are shown in figure 2. Jets from boosted W and Z decays are expected to generate peaks at  $m_j \approx 80$  and  $m_j \approx 90$  GeV, respectively. Jets from boosted H decays are expected to peak at  $m_j \approx 120$  GeV. Hadronic top-quark jets, where the b quark and the two different light quarks from the  $t \rightarrow Wb \rightarrow q\bar{q}'b$  decay are required to be within a reconstructed CA8 jet, peak at  $m_j \approx 175$  GeV. The peak around 20 GeV arises from unmerged light jets, mostly associated with quark- and gluon-induced jets from multijet events, but also from quark jets from W, Z, and H bosons in the cases where the decay products do not end up in a single jet. The contribution from bosons depends on their spin and polarization. All peaks are slightly shifted to lower masses because of the removal of soft radiation in jet pruning. If the pruned jet has a mass ( $m_j$ ) within  $70 < m_j < 100$  GeV/ $c^2$  ( $110 < m_j < 135$  GeV/ $c^2$ ), it is tagged as a W/Z (H) candidate.

Jet pruning can also provide a good delineation of subjets within the CA8 jet.



**Figure 2.** Distribution of pruned jet mass in simulation of signal and background processes. All simulated distributions are normalized to 1. The W/Z, H, and top-quark jets are required to match respective generator level particles in the event. The W/Z and H jets are from 1.5 TeV  $W' \rightarrow WH$  and  $Z' \rightarrow ZH$  signal samples.

To tag jets from  $H \rightarrow b\bar{b}$  decays, denoted as  $H_{bb}$  jets, the pruned subjets, given by reversing the last step of the CA8 pruning recombination algorithm, are used as the basis for b tagging. Jets arising from the hadronization of b quarks (b jets) are identified using the “Combined Secondary Vertex” b-tagging algorithm [49], which uses information from tracks and secondary vertices associated with jets to build a likelihood-based discriminator to distinguish between jets from b quarks and those from charm or light quarks and gluons. The b-tagging discriminator can take values between 0 and 1 with higher values indicating higher probability for the jet to originate from a b quark. The “loose” working point of the b-tagging algorithm [49] is chosen and is found to be optimal for both subjet and jet b tagging. It has a b-tagging efficiency of  $\approx 85\%$ , with mistagging probabilities of  $\approx 40\%$  for c-quark jets and  $\approx 10\%$  for light-quark and gluon jets at jet  $p_T$  near 80 GeV. The ratio of b-tagging efficiencies for data and simulation is applied as a scale factor [22] to the simulated signal events. To identify CA8 jets originating from  $H \rightarrow b\bar{b}$  decays, we apply b tagging either to the two subjets or to the CA8 jet, based on the angular separation of the two subjets ( $\Delta R$ ) [22]. If  $\Delta R$  is larger (smaller) than 0.3, the b-tagging algorithm is applied to both of the subjets (the single CA8 jet).



While the pruned jet mass is a powerful discriminant against QCD multijet backgrounds, the substructure of jets arising from  $V$  and  $H$  decays provides additional discrimination. In  $H \rightarrow WW^* \rightarrow 4q$  decays, the boosted  $H$  decays into a final state of four quarks merged together, denoted as an  $H_{WW}$  jet, and has a different substructure than jets from  $V/H \rightarrow \bar{q}q'$  decays. We quantify how well the constituents of a given jet can be arranged into  $N$  subjets by reconstructing the full set of jet constituents (before pruning) with the  $k_T$  algorithm [50] and halting the reclustering when  $N$  distinguishable protojets are formed. The directions of the  $N$  jets are used as the reference axes to compute the  $N$ -subjettiness [51–53]  $\tau_N$  of the original jet, defined as

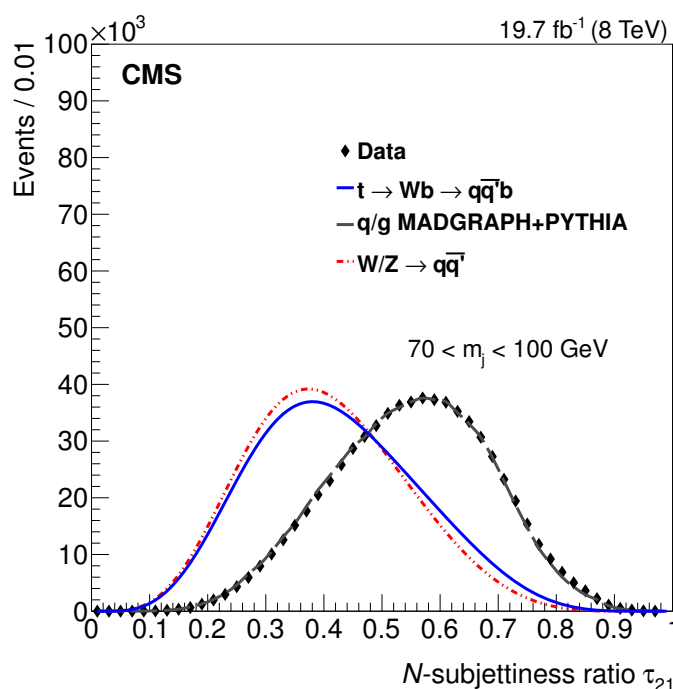
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}), \quad (4.1)$$

where  $p_{T,k}$  is the  $p_T$  of the  $k^{th}$  constituent of the original jet and  $\Delta R_{n,k}$  is its angular distance from the axis of the  $n$ th subjet (with  $n = 1, 2, \dots, N$ ). The normalization factor  $d_0$  for  $\tau_N$  is  $d_0 = \sum_k p_{T,k} R_0$ , with  $R_0$  set to 0.8, the distance parameter of the CA algorithm. To improve the discriminating power, we perform a one-pass optimization of the directions of the subjets' axes by minimizing  $\tau_N$  [24, 52]. By using the smallest  $\Delta R_{n,k}$  to weight the value of  $p_{T,k}$  in eq. (4.1),  $\tau_N$  yields small values when the jet originates from the hadronization of  $N$  or fewer quarks. The  $\tau_{ij} = \tau_i/\tau_j$  ratios  $\tau_{21}$ ,  $\tau_{31}$ ,  $\tau_{32}$ ,  $\tau_{41}$ ,  $\tau_{42}$ , and  $\tau_{43}$  have been studied to identify the best discriminators for jets from  $W/Z \rightarrow \bar{q}q'$  and  $H \rightarrow WW^* \rightarrow 4q$  decays.

We find that  $\tau_{21}$  is the most suitable variable for identifying  $W/Z \rightarrow \bar{q}q'$  jets [12]. The distribution of  $\tau_{21}$  for the  $W/Z \rightarrow \bar{q}q'$  signal, shown in figure 3, peaks below 0.4 and is almost fully contained within  $\tau_{21} < 0.75$ , where we place our cut. In contrast, the QCD background peaks around 0.6. The figure shows only  $W/Z$  candidate jets with the pruned jet mass in the  $W/Z$  boson mass window. For this reason, the jets matched to the top quark are mostly true  $W$  bosons, and appear signal-like. However, they represent only a small fraction of the top quarks from  $t\bar{t}$  events (cf. figure 2), since in the kinematic regime considered in this search, the top quarks are highly boosted and the  $b$  jet rarely fails to merge with the  $W$  jet. The overall contribution from  $t\bar{t}$ , after the full selection, is 1–3%.

For  $H \rightarrow WW^* \rightarrow 4q$  events, we find that the ratio  $\tau_{42}$  works best to discriminate between four-pronged  $H \rightarrow WW^* \rightarrow 4q$  and QCD jets. The discriminating power of  $\tau_{42}$  can be seen in figure 4. The  $\tau_{42}$  distribution of  $H_{WW}$  jets tends to peak around 0.55. By contrast,  $\tau_{42}$  distributions of multijet background and  $W/Z$  jets have a larger fraction of events at large values of  $\tau_{42}$ , especially after requiring a pruned jet mass in the range [110, 135] GeV. Jets from unmatched  $t\bar{t}$  events peak together with QCD jets, since they contain a mixture of  $b$ -quark jets and  $W$ -jets, but relatively few fully merged top-quark jets. However, the  $\tau_{42}$  distribution for matched top-quark jets tends to peak at smaller values, since for the same jet  $\tau_{42}$  is nearly always less than  $\tau_{32}$ , which is small for hadronic top-quark jets.

In figure 4, the comparison between dijet data and the QCD multijet simulation shows that the simulated distribution is well reproduced, though shifted towards higher values of  $\tau_{42}$  as compared with the data. A similar level of disagreement is known for the modelling

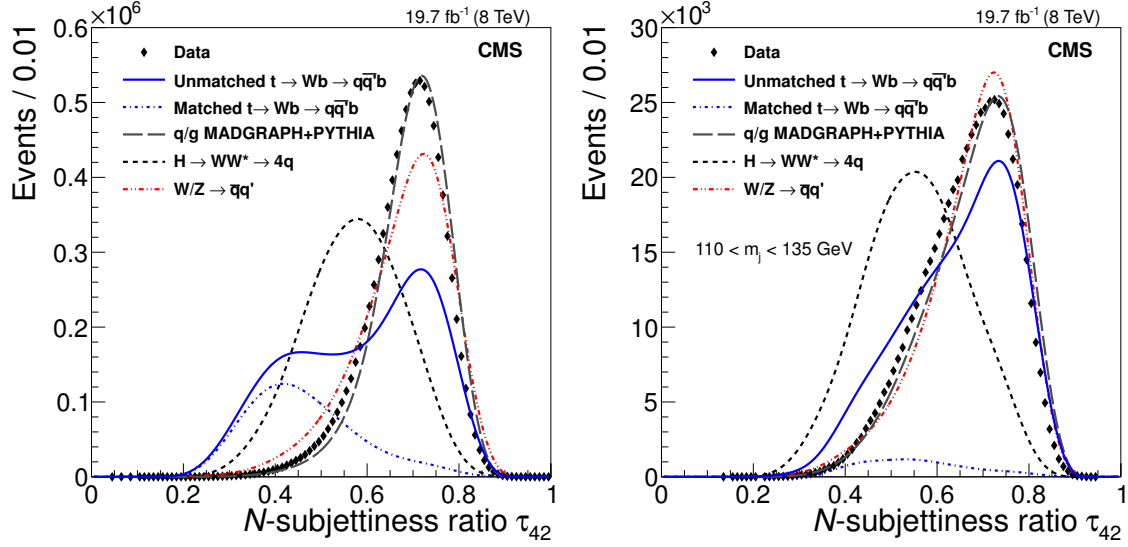


**Figure 3.** Distribution of the  $N$ -subjettiness ratio  $\tau_{21} = \tau_2/\tau_1$ , where  $\tau_N$  is given in eq. (4.1), for simulated signal and background processes, and for data. The jets for which  $\tau_{21}$  is calculated are required to satisfy the W/Z pruned jet mass requirement. The W/Z and top-quark jets are required to match respective generator level particles in the event. All simulated distributions are scaled to the number of events in data.

of  $\tau_{21}$  in QCD simulation in ref. [12]. The disagreement does not affect this analysis since the background is estimated from data. For the signal scale factor, the uncertainties from the modelling of  $\tau_{42}$  are taken into account.

We select “high (low)-purity” W/Z jets by requiring  $\tau_{21} \leq 0.5$  ( $0.5 < \tau_{21} < 0.75$ ), denoted as the HP (LP) V tag. Given the shape of  $\tau_{21}$  distribution for the W/Z signal, the HP V tag category has a higher efficiency than the LP V tag category. We select HP (LP)  $H_{WW}$  jets by requiring  $\tau_{42} \leq 0.55$  ( $0.55 < \tau_{42} < 0.65$ ), denoted as the HP (LP) H tag. Here also the HP category has a higher efficiency than the LP category.

Cross-talk between the H decay channels is possible; for example, two-pronged H decays (e.g.  $H \rightarrow b\bar{b}$ ,  $H \rightarrow c\bar{c}$ ) can be reconstructed as four-pronged  $H \rightarrow WW^* \rightarrow 4q$ , as shown in figure 5. Because of its large branching fraction,  $H \rightarrow b\bar{b}$  contributes a non-negligible number of events to the  $H \rightarrow WW^* \rightarrow 4q$  tagged sample. In order to combine events from  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow 4q$  channels into a single joint likelihood, these categories must be mutually exclusive. Since the  $H \rightarrow b\bar{b}$  tagger has significantly lower background than  $H \rightarrow WW^* \rightarrow 4q$ , it takes precedence in selecting events. We first identify the events that pass the  $H \rightarrow b\bar{b}$  tagger, and only if they fail we test them for the presence of the  $H \rightarrow WW^* \rightarrow 4q$  tag. Thus we arrive at the final division of events into five mutually exclusive categories. These event categories and their nomenclature are summarized in table 1.



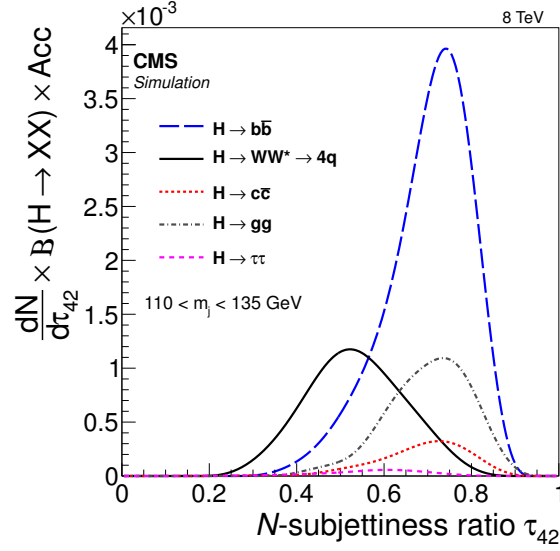
**Figure 4.** Distributions of  $\tau_{42}$  in data and in simulations of signal (2 TeV) and background events, without applying the pruned jet mass requirement (left) and with the pruned jet mass requirement applied (right). Matched top-quark, W/Z, and  $H_{WW}$  jets are required to be consistent with their generator level particles, respectively. All simulated distributions are scaled to the number of events in data, except that matched top-quark background is scaled to the fraction of unmatched  $t\bar{t}$  events times the number of data events.

Categories	V tag	H tag
$V^{\text{HP}}H_{bb}$	$\tau_{21} \leq 0.5$	b tag
$V^{\text{LP}}H_{bb}$	$0.5 < \tau_{21} < 0.75$	b tag
$V^{\text{HP}}H_{WW}^{\text{HP}}$	$\tau_{21} \leq 0.5$	$\tau_{42} \leq 0.55$
$V^{\text{LP}}H_{WW}^{\text{HP}}$	$0.5 < \tau_{21} < 0.75$	$\tau_{42} \leq 0.55$
$V^{\text{HP}}H_{WW}^{\text{LP}}$	$\tau_{21} \leq 0.5$	$0.55 < \tau_{42} < 0.65$

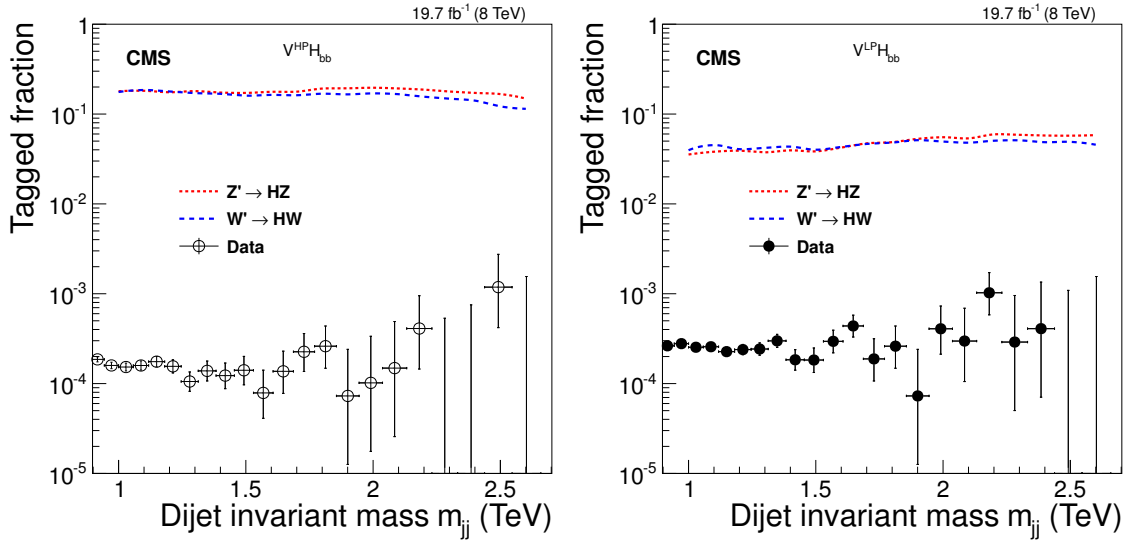
**Table 1.** Summary of event categories and their nomenclature used in the paper. The jet mass cut is  $70 < m_j < 100 \text{ GeV}/c^2$  for the V tag and  $110 < m_j < 135 \text{ GeV}/c^2$  for the H tag.

The LP V tag and LP H tag category is not included in this analysis, since it is dominated by background and therefore its contribution to the expected significance of the signal is negligible. Other H decay modes like  $H \rightarrow gg$ ,  $H \rightarrow \tau\tau$ ,  $H \rightarrow ZZ^*$ , and  $H \rightarrow c\bar{c}$  together contribute 2–7% of the total  $H \rightarrow b\bar{b}$  tagged events, and 18–24% of the total  $H \rightarrow WW^* \rightarrow 4q$  tagged events, as shown in figure 5. In this analysis, we only consider the  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow 4q$  channels. Other H channels passing the tagging requirements are conservatively viewed as background and included as systematic uncertainties, discussed in section 6.

The expected tag probabilities of the W, Z, and H selection criteria for signal and data events in different event categories are shown in figures 6 and 7, as a function of  $m_{jj}$ . The



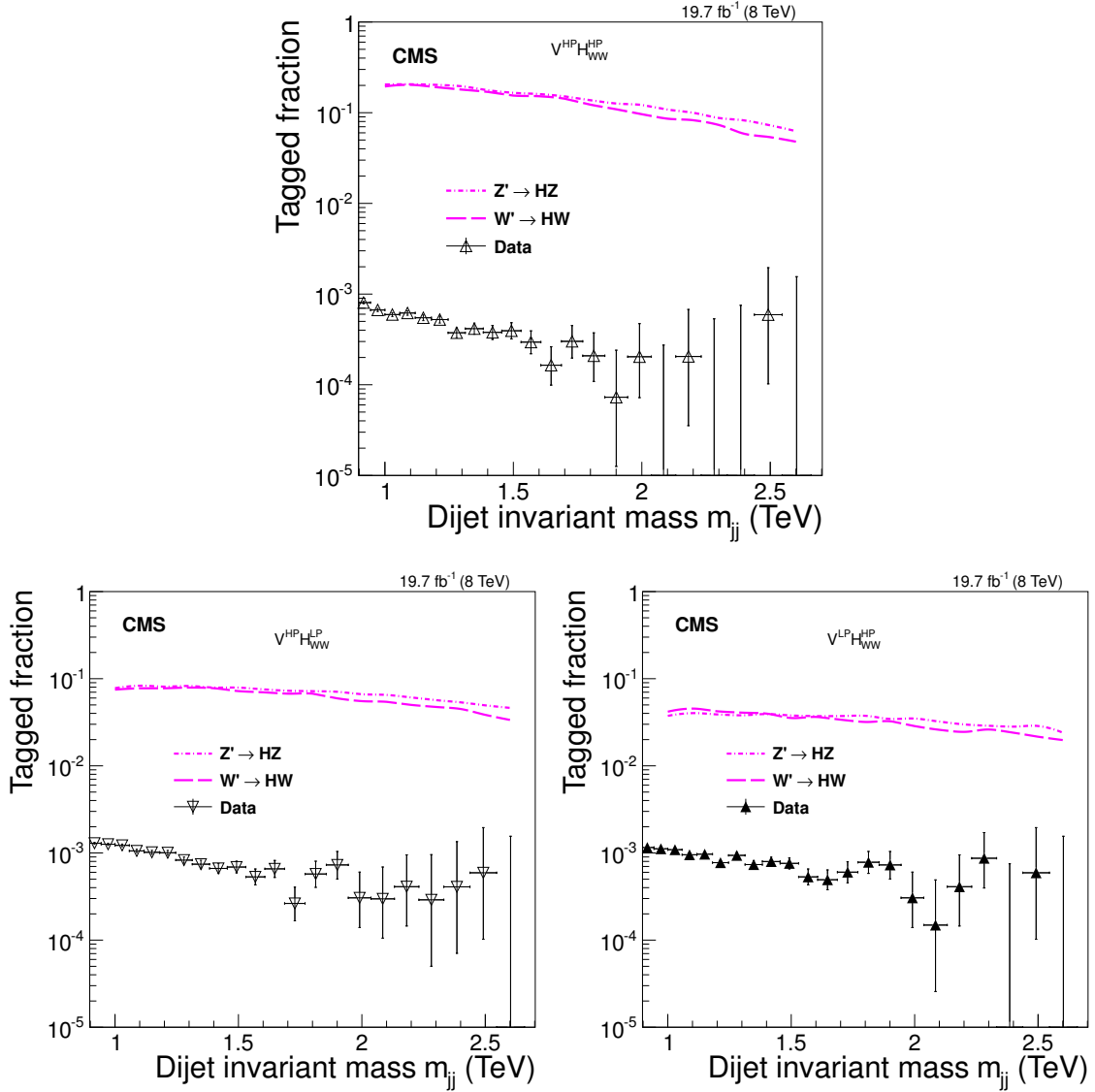
**Figure 5.** Comparison of  $\tau_{42}$  distributions for signal events failing the  $H \rightarrow b\bar{b}$  requirement. These events are from the  $H \rightarrow WW^* \rightarrow 4q$ ,  $H \rightarrow b\bar{b}$ ,  $H \rightarrow gg$ ,  $H \rightarrow c\bar{c}$ , and  $H \rightarrow \tau\tau$  channels. The  $H$  jets are from a 1.5 TeV resonance decaying to  $VH$ . All curves are normalized to the product of the corresponding branching fraction and acceptance.



**Figure 6.** Tagged fractions in  $H \rightarrow b\bar{b}$ ,  $W/Z \rightarrow \bar{q}q'$  signal channels and data as a function of dijet invariant mass, for categories of  $V^{HP}H_{bb}$  (left) and  $V^{LP}H_{bb}$  (right). Horizontal bars through the data points indicate the bin width.

$W/Z$  and  $H \rightarrow WW^* \rightarrow 4q$  tagging efficiencies for signal events in the  $H \rightarrow WW^* \rightarrow 4q$  categories fall at high  $p_T$ , primarily because the  $\tau_{42}$  distribution is  $p_T$ -dependent.

The Monte Carlo modelling of V-tag efficiency is validated using high- $p_T$   $W \rightarrow \bar{q}q'$  decays selected from a data sample enriched in semileptonic  $t\bar{t}$  events [24]. Scale factors of  $0.86 \pm 0.07$  and  $1.39 \pm 0.75$  are applied to the simulated events in the HP and LP V tag



**Figure 7.** Tagged fractions in  $H \rightarrow WW^* \rightarrow 4q$ ,  $W/Z \rightarrow \bar{q}q'$  signal channels and data as a function of dijet invariant mass, for categories of  $V^{HP}H_{WW}^{HP}$  (top),  $V^{HP}H_{WW}^{LP}$  (bottom left) and  $V^{LP}H_{WW}^{HP}$  (bottom right). Horizontal bars through the data points indicate the bin width.

categories, respectively, to match the tagging efficiencies in the top pair data. The decay of  $H \rightarrow WW^* \rightarrow 4q$  produces a hard  $W$  jet accompanied by two soft jets from the off-shell  $W$  boson. As the  $H \rightarrow WW^* \rightarrow 4q$  tagger is also based on the  $N$ -subjettiness variables, and the measured ratio  $\tau_{42}/\tau_{21}$  is well modelled by QCD simulation, it is reasonable to assume that the mismodelling of the shower by PYTHIA is similar to that in the case of  $V$  tagging. The  $H \rightarrow WW^* \rightarrow 4q$  tagging efficiency scale factors are extrapolated using the same technique as for  $V$  tagging for both the HP and LP categories, respectively, with additional systematic uncertainties, which are discussed in section 6.

## 5 Resonance search in the dijet mass spectrum

The resolution for the  $m_{jj}$  reconstruction is in the range 5–10% for all the five categories. The dominant background in this analysis is from multijet events with an additional 1–3% contribution from  $t\bar{t}$  events. The background is modelled by a smoothly falling distribution for each event category, given by the empirical probability density function

$$P_D(m_{jj}) = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}. \quad (5.1)$$

The background model includes the small  $t\bar{t}$  background, which falls smoothly in a similar way to the multijet background.

Each event category has separate normalization  $P_0$  and shape parameters  $P_1$  and  $P_2$ . This parameterization was deployed successfully in a number of searches based on dijet mass spectra [46]. A Fisher F-test [54] is used to check that no additional parameters are needed to model the individual background distributions, compared with the four-parameter function used in [46]. We have also tested an alternative function  $P_E(m_{jj}) = P_0/(m_{jj}/\sqrt{s} + P_1)^{P_2}$ , and found it less favored by the F-test.

The use of the alternative function in the analysis produces negligible changes in the final result and therefore, no systematic uncertainty is associated with this choice.

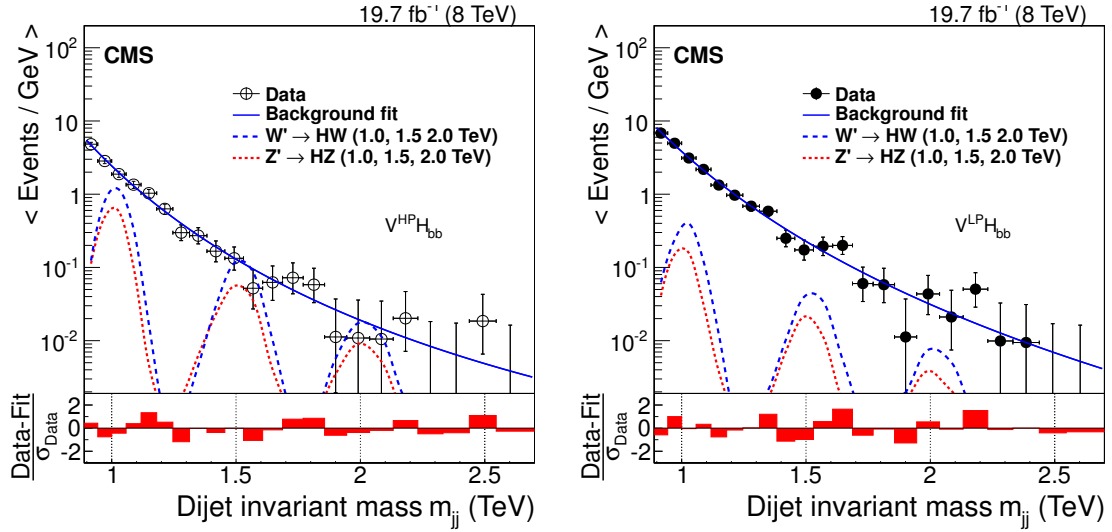
We search for a peak on top of the falling background spectrum by means of a binned maximum likelihood fit to the data.

The binned likelihood is given by

$$\mathcal{L} = \prod_i \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!}, \quad (5.2)$$

where  $\lambda_i = \mu N_i(S) + N_i(B)$ ,  $\mu$  is a scale factor for the signal,  $N_i(S)$  is the number of events expected from the signal, and  $N_i(B)$  is the number expected from multijet background. The variable  $n_i$  quantifies the number of observed events in the  $i^{\text{th}}$   $m_{jj}$  bin. The number of background events  $N_i(B)$  is described by the functional form of eq. (5.1). The signal shape for each narrow-width resonance hypothesis is obtained by fitting the  $m_{jj}$  distribution from simulated events with a sum of a Gaussian and a Crystal Ball probability density function. The resulting shape is fixed and, as such, used in the combined signal and background fit. This procedure is repeated for each resonance hypothesis, sampling resonance masses from 1.0 to 2.6 TeV in steps of 50 GeV. While maximizing the likelihood,  $\mu$  and the parameters of the background function are left unconstrained. The shape of the resonance is additionally modified to account for systematic uncertainties (described below); parameters controlling each source of systematic uncertainty are also allowed to vary in the fit, albeit within constraints. For presentational purposes, a binning according to  $m_{jj}$  resolution is used in this paper. However, the likelihood is calculated in bins of 1 GeV in  $m_{jj}$ , approximating an unbinned analysis, while keeping it computationally manageable.

Figures 8 and 9 show the  $m_{jj}$  distributions in data. The solid curves represent the results of the maximum likelihood fit to the data, fixing the number of expected signal



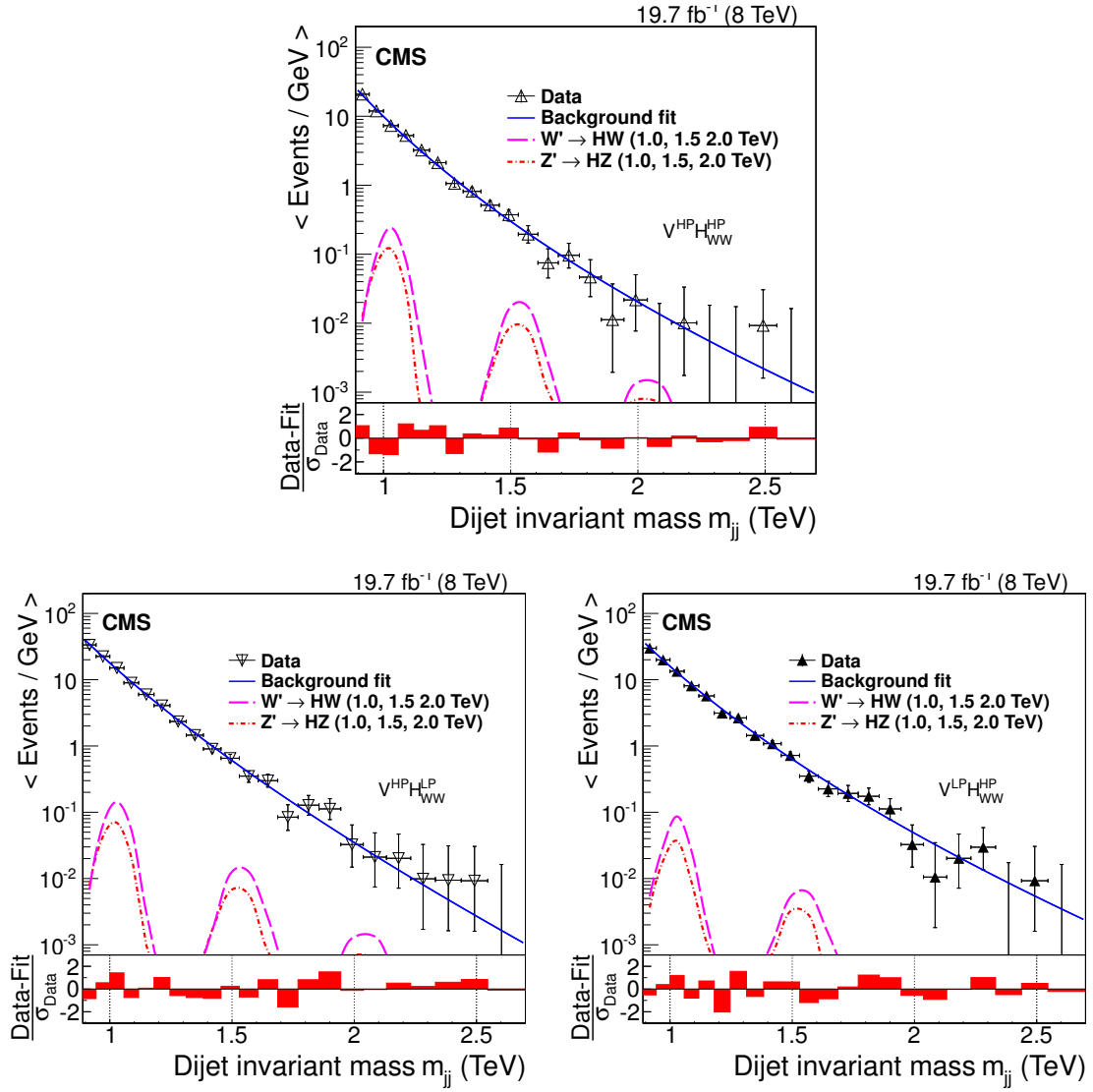
**Figure 8.** Distributions in  $m_{jj}$  are shown for  $V^{\text{HP}}H_{bb}$  category (left),  $V^{\text{LP}}H_{bb}$  category (right). The solid curves represent the results of fitting eq. (5.1) to the data. The distributions for  $H \rightarrow b\bar{b}$ ,  $W/Z \rightarrow \bar{q}q'$  contributions, scaled to their corresponding cross sections, are given by the dashed curves. The vertical axis displays the number of events per bin, divided by the bin width. Horizontal bars through the data points indicate the bin width. The corresponding pull distributions  $\frac{\text{Data}-\text{Fit}}{\sigma_{\text{Data}}}$ , where  $\sigma_{\text{Data}}$  represents the statistical uncertainty in the data in a bin in  $m_{jj}$ , are shown below each  $m_{jj}$  plot.

events to zero, while the bottom panels show the corresponding pull distributions, quantifying the agreement between the background-only hypothesis and the data. The expected distributions of  $H \rightarrow b\bar{b}$ ,  $W/Z \rightarrow \bar{q}q'$  and  $H \rightarrow WW^* \rightarrow 4q$ ,  $W/Z \rightarrow \bar{q}q'$  signals at 1.0, 1.5 and 2.0 TeV in each category, scaled to their corresponding cross sections are given by the dashed and dash-dotted curves. The resonance masses in  $VH_{bb}$  channels are slightly lower than those of the  $VH_{WW}$  channels because of missing neutrinos in b-hadron decays and partial misreconstruction of two-pronged  $H \rightarrow b\bar{b}$  decays.

## 6 Systematic uncertainties

The largest contributions to the systematic uncertainty are associated with the modelling of the signal, namely: the efficiencies of W/Z, H, and b tagging; the choice of PDF; the jet energy scale (JES); the jet energy resolution (JER); the pileup corrections; the cross-talk between different signal contributions; and the integrated luminosity.

The uncertainty in the efficiency for W/Z tagging is estimated using a control sample enriched with  $t\bar{t}$  events described in ref. [24]. Uncertainties of 7.5% and 54% in the respective scale factors for HP and LP V tag include contributions from control-sample statistical uncertainties, and the uncertainties in the JES and JER for pruned jets [12]. The uncertainty due to the extrapolation of the simulated W/Z-tagging efficiency to higher jet  $p_T$  is estimated by studying the W/Z-tagging efficiency as a function of  $p_T$  for two different



**Figure 9.** Distributions in  $m_{jj}$  are shown for  $V^{HP}H_{WW}^{HP}$  (top),  $V^{HP}H_{WW}^{LP}$  (bottom left), and  $V^{LP}H_{WW}^{HP}$  (bottom right). The solid curves represent the results of fitting eq. (5.1) to the data. The distributions for  $H \rightarrow WW^* \rightarrow 4q$ ,  $W/Z \rightarrow \bar{q}q'$  contributions, scaled to their corresponding cross sections, are given by the dashed and dash-dotted curves. The vertical axis displays the number of events per bin, divided by the bin width. Horizontal bars through the data points indicate the bin width. The corresponding pull distributions  $\frac{\text{Data-Fit}}{\sigma_{\text{Data}}}$ , where  $\sigma_{\text{Data}}$  represents the statistical uncertainty in the data in a bin in  $m_{jj}$ , are shown below each  $m_{jj}$  plot.

showering and hadronization models using PYTHIA 6 and HERWIG++, respectively. The results show that the differences are within 4% (12%) for the HP (LP) V tagging [24].

We extrapolate the  $H \rightarrow WW^* \rightarrow 4q$  tagging efficiency scale factor in the same way as the W/Z-tagging efficiency, with an additional systematic uncertainty based on the difference between PYTHIA 6 and HERWIG++ in modelling  $H \rightarrow WW^* \rightarrow 4q$  decay. This is evaluated to be  $\approx 7\%$  for the HP and LP H tag. The uncertainty from the pruned jet mass



Signal/Categories	$V^{\text{HP}}H_{\text{bb}}$	$V^{\text{LP}}H_{\text{bb}}$	$V^{\text{HP}}H_{\text{WW}}^{\text{HP}}$	$V^{\text{HP}}H_{\text{WW}}^{\text{LP}}$	$V^{\text{LP}}H_{\text{WW}}^{\text{HP}}$
$H \rightarrow b\bar{b}, Z \rightarrow q\bar{q}$	$2.3 \times 10^{-2}$	$4.8 \times 10^{-3}$	$1.0 \times 10^{-3}$	$1.6 \times 10^{-3}$	$3.9 \times 10^{-4}$
$H \rightarrow WW^* \rightarrow 4q, Z \rightarrow q\bar{q}$	$5.6 \times 10^{-4}$	$\approx 0$	$2.6 \times 10^{-3}$	$9.8 \times 10^{-4}$	$4.5 \times 10^{-4}$

**Table 2.** Summary of the values  $P$  for a  $Z'$  signal at 1.5 TeV resonance mass and the corresponding background yield in all five categories.

requirement in the  $H \rightarrow WW^* \rightarrow 4q$  search is already included in the extrapolated scale factor uncertainty of the V-tag.

The uncertainty in the efficiency of  $H \rightarrow b\bar{b}$  tagging can be separated into two categories: the efficiency related to the  $b$  tagging and the efficiency related to the pruned  $H$  mass tag. The first is obtained by varying the  $b$ -tagging scale factors within the associated uncertainties [22] and amounts to 15%. The second is assumed to be similar to the mass selection efficiency of  $W$  jets estimated in ref. [24], additionally accounting for the difference in fragmentation of light quarks and  $b$  quarks, which amounts to 2.6% per jet.

Because of the rejection of charged particles not originating from the primary vertex, and the application of pruning, the dependence of the  $W/Z$ - and  $H$ -tagging efficiencies on pileup is weak and the uncertainty in the modelling of the pileup distribution is  $\leq 1.5\%$  per jet.

In this analysis, we only consider  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow 4q$  decays. Other  $H$  decay channels that pass  $H$  taggers are viewed as nuisance signals, and a corresponding cross-talk systematic uncertainty is assigned. We evaluate this uncertainty as a ratio of expected nuisance signal events with respect to the total expected signal events, taking into account the branching fractions, acceptances and tagging efficiencies. The contamination from cross-talk is estimated to be 2–7% in the  $VH_{\text{bb}}$  categories, and 18–24% in the  $VH_{\text{WW}}$  categories, and we take the maximum as the uncertainty. The analysis is potentially 7% (24%) more sensitive than quoted, but since it is not clear how well the efficiency for the nuisance signals is understood, they are neglected, yielding a conservative limit on new physics. When the  $VH_{\text{bb}}$  and  $VH_{\text{WW}}$  categories are combined together, the 24% uncertainty becomes a small effect, based on a quantitative measure of sensitivity suggested in ref. [55]:

$$P = \frac{\mathcal{B}(H \rightarrow XX) \epsilon_S}{1 + \sqrt{N_B}} \quad (6.1)$$

where  $\mathcal{B}(H \rightarrow XX)$  is the branching fraction for the  $H$  decay channel,  $\epsilon_S$  is the signal tagging efficiency, and  $N_B$  is the corresponding background yield. The values of  $P$  for each channel are shown in table 2.

The JES has an uncertainty of 1–2% [44, 56], and its  $p_T$  and  $\eta$  dependence is propagated to the reconstructed value of  $m_{\text{jj}}$ , yielding an uncertainty of 1%, independent of the resonance mass. The impact of this uncertainty on the calculated limits is estimated by changing the dijet mass in the analysis within its uncertainty. The JER is known to a precision of 10%, and its non-Gaussian features observed in data are well described by the CMS simulation [44]. The effect of the JER uncertainty on the limits is estimated by changing

Source	HP uncertainties (%)	LP uncertainties (%)
JES	1	1
JER	10	10
Pileup	$\leq 3.0$	$\leq 3.0$
PDF	5–15	5–15
Integrated luminosity	2.6	2.6
W tagging	7.5	54
W tag $p_T$ dependence	4	12

**Table 3.** Systematic uncertainties common to all categories.

Source	Final state		
	$H \rightarrow b\bar{b}$		$H \rightarrow WW^* \rightarrow 4q$
	$VH_{bb}$	$VH_{WW}$	$VH_{WW}$
$H \rightarrow b\bar{b}$ mass scale	2.6	—	—
H(4q) tagging	—	7.5 (54)	7.5 (54)
H(4q)-tag $\tau_{42}$ extrapolation	—	7	7
Cross-talk	7	24	24
b tagging	$\leq 15$	$\leq 15$	—

**Table 4.** Systematic uncertainties(%) for  $X \rightarrow VH$  signals, in which  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow 4q$ . Numbers in parentheses represent the uncertainty for the corresponding LP category. If LP has the same uncertainty as HP, only the HP uncertainty is presented here.

the reconstructed resonance width within its uncertainty. The integrated luminosity has an uncertainty of 2.6% [57], which is also taken into account in the analysis.

The uncertainty related to the PDF used to model the signal acceptance is estimated from the CT10 [58], MSTW08 [59], and NNPDF21 [60] PDF sets. The envelope of the upward and downward variations of the estimated acceptance for the three sets is assigned as uncertainty [61] and found to be 5–15% in the resonance mass range of interest. A summary of all systematic uncertainties is given in table 3 and 4. Among these uncertainties, the JES and JER are applied as shape uncertainties, while others are applied as uncertainty in the event yield.

## 7 Results

The asymptotic approximation [62] of the LHC  $CL_s$  criterion [63, 64] is used to set upper limits on the cross section for resonance production. The dominant sources of systematic uncertainties are treated as nuisance parameters associated with log-normal priors in those variables. For a given value of the signal cross section, the nuisance parameters are fixed to the values that maximize the likelihood, a method referred to as profiling. The dependence of the likelihood on parameters used to describe the background in eq. (5.1) is treated in the

Process	Observed lower mass limit (TeV)	Expected lower mass limit (TeV)
$W' \rightarrow HW$	[1.0, 1.6]	1.7
$Z' \rightarrow HZ$	[1.0, 1.1], [1.3, 1.5]	1.3
$V' \rightarrow VH$	[1.0, 1.7]	1.9

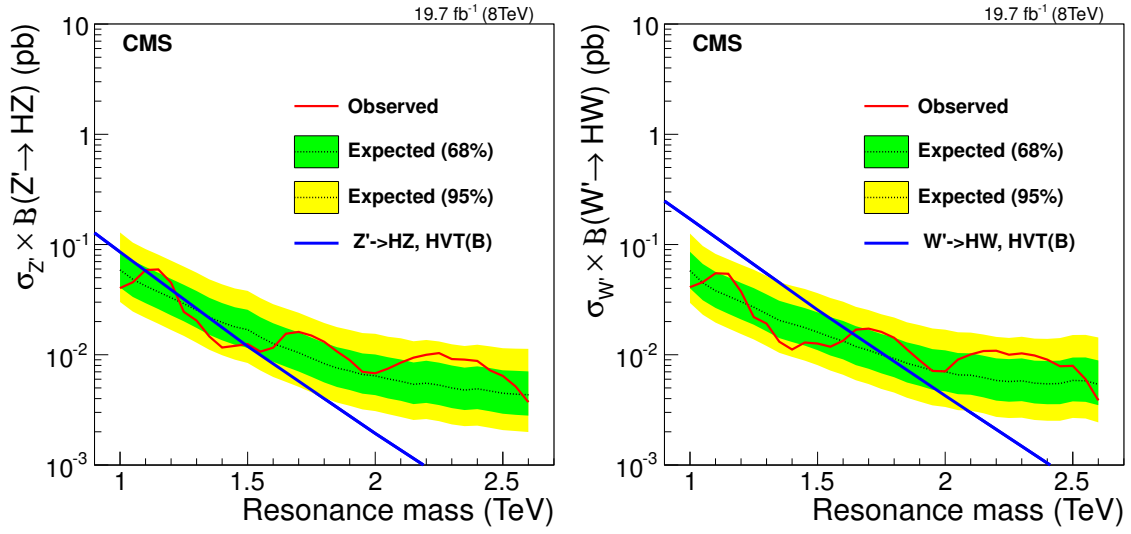
**Table 5.** Summary of observed lower limits on resonance masses at 95% CL and their expected values, assuming a null hypothesis. The analysis is sensitive to resonances heavier than 1 TeV.

same manner, and no additional systematic uncertainty is assigned to the parameterization of the background.

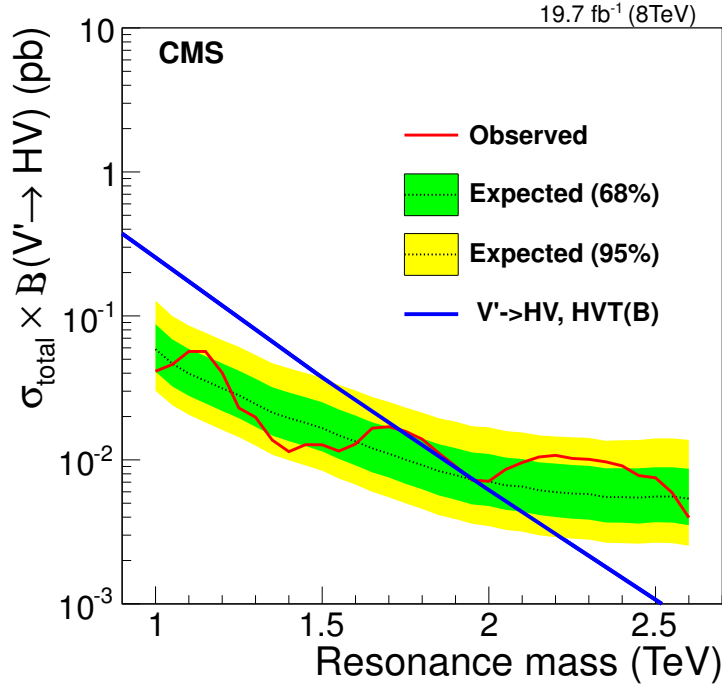
Events from the 5 categories of table 1 are combined into a common likelihood, with the uncertainties of the HP and LP H tag (V tag) efficiencies considered to be anticorrelated between HP and LP tagging because events failing the HP  $\tau_{42}$  ( $\tau_{21}$ ) selection migrate to the LP category and the fraction of events failing both HP and LP requirements is small compared to the HP and LP events. The branching fractions of  $H \rightarrow WW^* \rightarrow 4q$  and  $H \rightarrow b\bar{b}$  decays are taken as fixed values in joint likelihood. The remaining systematic uncertainties in the signal are fully correlated across all channels. The variables describing the background uncertainties are treated as uncorrelated. Figure 10 shows the observed and background-only expected upper limits on the production cross sections for  $Z'$  and  $W'$ , including both  $H \rightarrow b\bar{b}$  and  $H \rightarrow WW^* \rightarrow 4q$  decays, computed at 95% confidence level (CL), with the predicted cross sections for the benchmark models overlaid for comparison. In the HVT model scenario B,  $W'$  and  $Z'$  are degenerate in resonance mass, thus we compute the limit on their combined cross section under this hypothesis, shown in figure 11. Table 5 shows the exclusion ranges on resonance masses.

## 8 Summary

A search for a massive resonance decaying into a standard model-like Higgs boson and a W or Z boson is presented. A data sample corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$  collected in proton-proton collisions at  $\sqrt{s} = 8 \text{ TeV}$  with the CMS detector has been used to measure the W/Z and Higgs boson-tagged dijet mass spectra using the two highest  $p_T$  jets within the pseudorapidity range  $|\eta| < 2.5$  and with pseudorapidity separation  $|\Delta\eta| < 1.3$ . The QCD background is suppressed using jet substructure tagging techniques, which identify boosted bosons decaying into hadrons. In particular, the mass of pruned jets and the  $N$ -subjettiness ratios  $\tau_{21}$  and  $\tau_{42}$ , as well as b tagging applied to the subjects of the Higgs boson jet, are used to discriminate against the otherwise overwhelming QCD background. The remaining QCD background is estimated from a fit to the dijet mass distributions using a smooth function. We have searched for the signal as a peak on top of the smoothly falling QCD background. No significant signal is observed. In the HVT model B, a  $Z'$  is excluded in resonance mass intervals [1.0, 1.1] and [1.3, 1.5] TeV, while a  $W'$  is excluded in the interval [1.0, 1.6] TeV. A mass degenerate  $W'$  plus  $Z'$  particle is excluded in the interval [1.0, 1.7] TeV.



**Figure 10.** Expected and observed upper limits on the production cross sections for  $Z' \rightarrow HZ$  (left) and  $W' \rightarrow HW$  (right), including all five decay categories. Branching fractions of H and V decays have been taken into account. The theoretical predictions of the HVT model scenario B are also shown.



**Figure 11.** Expected and observed upper limits on the production cross section for  $V' \rightarrow VH$ , obtained by combining  $W'$  and  $Z'$  channels together. Branching fractions of H and V decays have been taken into account. The theoretical prediction of the HVT model scenario B is also shown.

This is the first search for heavy resonances decaying into a Higgs boson and a vector boson (W/Z) resulting in a hadronic final state, as well as the first application of jet substructure techniques to identify  $H \rightarrow WW^* \rightarrow 4q$  decays of the Higgs boson at high Lorentz boost.

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